

An Early-Time Infrared and Optical Study of the Type Ia Supernova 1998bu in M 96 1

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ABSTRACT

We present first-season infrared (IR) and optical photometry and spectroscopy

of the Type Ia Supernova 1998bu in M 96. We also report optical polarimetry of this event. SN 1998bu is one of the closest type Ia Supernovae of modern times and the distance of its host galaxy is well-determined. We find that SN 1998bu is both photometrically and spectroscopically normal. However, the extinction to this event is unusually high, with $A_V = 1.0 \pm 0.11$. We find that SN 1998bu peaked at an intrinsic $M_V = -19.37 \pm 0.23$. Adopting a distance modulus of 30.25 (Tanvir *et al.* 1999) and using Phillips *et al.*'s (1999) relations for the Hubble constant we obtain $H_0 = 70.4 \pm 4.3$ km/s/Mpc. Combination of our IR photometry with those of Jha *et al.* (1999) provides one of the most complete early-phase IR light curves for a SN Ia published so far. In particular, SN 1998bu is the first normal SN Ia for which good pre- t_{Bmax} IR coverage has been obtained. It reveals that the J , H and K light curves peak about 5 days earlier than the flux in the B -band curve.

Key words: Supernovae: SN 1998bu - photometry - spectroscopy.

1 INTRODUCTION

Supernova 1998bu appeared in the Leo I group Sab galaxy M 96 (NGC 3368) and was discovered by Mirko Villi (1998) on May 9.9 UT at a magnitude of about +13 (unfiltered CCD), 10 days before maximum blue light, t_{Bmax} =May 19.8 \pm 0.5 UT (see below). It is located in one of the spiral arms and has an offset of 4".3E, 55".3N from M 96's nucleus (Villi 1998). The supernova was identified by Ayani *et al.* (1998) and Meikle *et al.* (1998) as being of type Ia. Its position is RA: 10h 46m 45.95s, Dec:+11° 50' 07.1" (2000.0). This position was determined by us, using a V-band image taken with the Wide Field Camera of the Isaac Newton Telescope. Our value agrees with the positions reported by Nakano & Aoki (1998) and Boschini (1998) to within 1."2. An R -band image of SN 1998bu is shown in Figure 1.

A pre-discovery observation on May 3.14 UT was reported by Faranda & Skiff (1998). This was about 16.5 days before t_{Bmax} making it one of the earliest ever observations of a type Ia supernova (Riess *et al.* 1999). The Faranda & Skiff measurement was made with an unfiltered CCD, and converts to magnitude increments relative to the B and V maxima of +4.65 \pm 0.18 and +4.75 \pm 0.15 respectively (Riess *et al.* 1999). These are the largest magnitude increments ever measured for the rising portion of a type Ia event. Riess *et al.* (1999) estimate a B-band rise-time of 19.5 \pm 0.2 days for a typical SN Ia. This implies an explosion date for SN 1998bu of 1998 April 30.2 \pm 0.5 UT.

An important aspect of the discovery of this supernova is that HST images already exist for its parent galaxy M 96. Thus, Cepheids found in these images can be used to find its distance. Tanvir *et al.* (1995) obtained a distance modulus of 30.32 ± 0.15 . Addition of the 0.05 mag “long-vs-short exposure” correction (Casertano & Mutchler 1998; Gibson *et al.* 2000) increases this to 30.37 ± 0.16 . This is the value included in Parodi *et al.*’s (2000) estimate of H_0 based on SN Ia observations. However, Tanvir *et al.* (1999) have revised their estimate using a larger number of Cepheids (16 as against 7) in M 96 and applying a correction for metallicity differences between the LMC and M 96. They obtain 30.25 ± 0.18 . Gibson *et al.* (2000) use 11 Cepheids in M 96 to find its distance. Including their “typical correction factor” of +0.07 mag for metallicity difference between their six principal host galaxies and the LMC, they obtain a modulus of $30.27 \pm 0.10_{rand.} \pm 0.16_{sys.}$ for M 96. This is in good agreement with Tanvir *et al.* (1999). In this paper, we adopt the distance modulus of Tanvir *et al.* *viz.* 30.25 ± 0.18 or a distance of 11.2 ± 1.0 Mpc. SN 1998bu is one of the closest type Ia’s of modern times, as well as being observed from an exceptionally early epoch.

We note that Feldmeier *et al.* (1997) estimated the M 96 distance modulus using the Planetary Nebula Luminosity Function Method (PNLF) and found a significantly smaller distance modulus of 29.91 ± 0.13 . However, Ferrarese *et al.* (2000) have commented on the tendency of the PNLf method to produce systematically shorter distances than does the use of Cepheids (or, indeed, the use of the Tip of the Red Giant Branch method or the Surface Brightness Fluctuation method). We therefore do not make use of the Feldmeier *et al.* value.

Type Ia SNe are increasingly recognized as being among the most reliable indicators of cosmological distances (*cf.* Hamuy *et al.* 1996, Riess *et al.* 1996, Perlmutter *et al.* 1997). However, calibration of the zero point requires nearby, well-observed SNe Ia at accurately known distances. Such events are quite rare, but SN 1998bu is one such example. A number of major studies of this event have been carried out. Suntzeff *et al.* (1999) gave a detailed description and analysis of the optical light curves acquired at the Cerro Tololo Inter-American Observatory (CTIO) and Las Campanas Observatory (LCO). Jha *et al.* (1999) presented and discussed optical and infrared photometry and spectroscopy of the event acquired at a number of telescopes.

In this paper, we describe IR and optical observations of SN 1998bu obtained at several telescopes. A preliminary report of this work is presented in Meikle & Hernandez (2000).

In Section 2 we describe our optical and infrared photometry and spectroscopy, plus optical polarimetry of SN 1998bu. In Section 3 the spectra and light curves are discussed. In Section 4 correction for extinction is determined and the peak absolute magnitudes for SN 1998bu are deduced. We use them to give a value for H_0 . A brief summary is given in Section 5.

2 OBSERVATIONS

2.1 Optical Photometry

Shortly after the discovery of SN 1998bu we began a programme of *UBVRI* imaging. Most of the data were obtained using the 82 cm Instituto de Astrofísica de Canarias Telescope (IAC80) on Tenerife, and the 1.0 m Jacobus Kapteyn Telescope (JKT) at La Palma Observatory. Some additional photometry was obtained at the 2.56 m Nordic Optical Telescope (NOT) (La Palma) and the 3.5 m Wyoming-Indiana-Yale-NOAO telescope (WIYN) at Kitt Peak. The earliest image was taken on May 13th (JD 2450947.43) at -5 days *i.e.* 5 days before the epoch of maximum blue light, t_{Bmax} . The first season optical photometry presented here spans 53 days.

The IAC80 observations were acquired with its 1024×1024 CCD camera (scale= $0.''433/\text{pixel}$, fov= 7.3×7.3 arcmin.). Its *BVRI* central wavelengths are 4500, 5250, 6000 and 8800 Å. The JKT observations were obtained using its 1024×1024 CCD camera (plate scale= $0.''331/\text{pixel}$, fov= 5.6×5.6 arcmin.). Its *UBVRI* filter transmission characteristics are very close to those of Johnson-Cousins. The central wavelengths are, respectively, 3600, 4350, 5350, 6450 and 8400 Å. The WIYN photometry was obtained with a 2048×2048 CCD (scale= $0.195''/\text{pix}$, fov= 6.5×6.5 arcmin.) and *UBVRI* filters centred at 3584, 4327, 5448, 6461 and 8387 Å respectively. At the NOT, TURPOL was used to obtain photopolarimetry in *BVRI*, with central wavelengths at 4400, 5300, 5900, and 8300 Å.

IAC80 data were reduced at the IAC using IRAF software. The reduction steps included bias-subtraction, flat-fielding and correction for bad pixels by interpolation. The reduction of the data from the NOT is described in Oudmaijer *et al.* (2000). Data from the other telescopes were reduced at Imperial College using the Starlink package CCDPACK to carry out the standard procedures of de-biasing, flat-fielding and bad-pixel and cosmic-ray removal. Aperture photometry was then carried out. The flux from the supernova or standard stars was measured in a circular aperture. The background was estimated and subtracted using an annulus concentric with the central aperture. The annulus inner and outer radii were

respectively $\times 1.5$ and $\times 2.5$ that of the central aperture. For a given night and telescope, the central aperture was selected to have a diameter equal to four times the FWHM of a typical stellar image. Owing to its spatial variation, particular care had to be taken in estimating and subtracting the background from the host galaxy. To check this, we examined *VRI* images of M 96 taken by N. Tanvir with the INT in 1994. We found that variation of the aperture annulus radius from $\sim 10''$ to $\sim 20''$, centred on the supernova position, would affect the supernova instrumental magnitudes presented here by no more than 0.01 mag. Instrumental magnitudes were then obtained using the Starlink PHOTOM package. Photometry was performed in two steps. First, the supernova magnitudes relative to comparison field stars were measured. The comparison stars were then calibrated against Landolt field stars. The comparison stars are identified as CS1, CS2, CS3, CS4 and CS5 in Figure 1. At least three of these were usually available on a given frame.

For the IAC80 observations, colour-corrected magnitude differences between the comparison stars and SN 1998bu were obtained using the canonical equations (1) *viz.*:

$$\begin{aligned}\Delta b &= \Delta b_o + C_b \Delta(b_o - v_o) \\ \Delta v &= \Delta v_o + C_v \Delta(b_o - v_o) \quad (1) \\ \Delta r &= \Delta r_o + C_r \Delta(v_o - r_o) \\ \Delta i &= \Delta i_o + C_i \Delta(r_o - i_o)\end{aligned}$$

where Δb_o , Δv_o , Δr_o , Δi_o are the instrumental magnitude differences between a comparison star and the supernova, $\Delta(b_o - v_o)$, $\Delta(v_o - r_o)$, $\Delta(r_o - i_o)$ are the colour differences, and C_b , C_v , C_r , C_i are the colour coefficients, derived below using the procedures of Hardie (1962). No airmass term appears since, for any frame, the comparison stars and supernova were observed at essentially the same airmass. The comparison stars were calibrated in *BVRI* using standard Landolt (1992) fields. The observations for this were carried out with the IAC80 on 1999 June 13. The colour correction coefficients were also derived from these data using IRAF's PHOTCAL package. The respective values for (C_b, C_v, C_r, C_i) were $(0.022 \pm 0.010, 0.014 \pm 0.007, 0.036 \pm 0.015, 0.075 \pm 0.020)$. These values agree well with those shown in the IAC80 web-page (<http://www.iac.es/telescopes/iac80/instrumentacion.html#color>).

For the WIYN observations, calibration of the comparison stars in *VRI* was carried out using Landolt standards observed at the WIYN telescope on 1998 June 5. Similar procedures

were used as for the IAC80 calibrations. However, no Landolt standards were observed in U or B . Therefore we used a modified version of equations (1) *viz.*:

$$\begin{aligned}\Delta v &= \Delta v_o + C'_v \Delta(v_o - r_o) \\ \Delta r &= \Delta r_o + C'_r \Delta(v_o - r_o) \quad (2) \\ \Delta i &= \Delta i_o + C'_i \Delta(r_o - i_o)\end{aligned}$$

Values for (C'_v, C'_r, C'_i) were found to be $(0.002 \pm 0.008, -0.014 \pm 0.018, 0.073 \pm 0.028)$.

The VRI comparison star magnitudes obtained from the IAC80 and WIYN all agreed to within the errors, and so the weighted mean values from these telescopes were adopted. The $BVRI$ comparison star magnitudes are shown in Table 1.

Unfortunately, in the case of the JKT the observations that were obtained of standard star fields did not span an adequate colour range. Moreover, the constraints of scheduled JKT observers meant that often only two or three filters were available, and in a variety of combinations. In view of this, we did not carry out colour corrections for the JKT data. Colour correction procedures, such as those described above, can alter the magnitude by as much as 0.1, with the U and B filters usually being the most sensitive to this effect. However, since our SN 1998bu magnitudes were obtained by averaging the values obtained relative to comparison stars of different colour indices, we expect the error due to inadequate colour correction to be small. Nevertheless, for such cases, we have increased the uncertainty to ± 0.075 .

We then used the calibrated magnitudes of the comparison stars (Table 1) to transform the colour-corrected differences from equations (1) or (2) into apparent magnitudes for SN1998bu using equations (3) *viz.*:

$$\begin{aligned}B_{sn} &= B_{cs} - \Delta b \\ V_{sn} &= V_{cs} - \Delta v \quad (3) \\ R_{sn} &= R_{cs} - \Delta r \\ I_{sn} &= I_{cs} - \Delta i\end{aligned}$$

Only a few U -band measurements were obtained. Moreover, due to the lack of observations of standard stars in this band, we had to indirectly calibrate the comparison stars. To achieve this, we used average U -band magnitudes for these stars from Jha *et al.* (1999)

Table 1. Magnitudes of Comparison Stars near SN1998bu

Star	B	V	R	I
CS1	13.607(18) ^a	13.092(10)	12.776(10)	12.481(13)
CS2	15.559(40)	15.039(15)	14.712(22)	14.393(25)
CS3	17.320(93)	16.509(30)	15.867(48)	15.277(55)
CS4	16.410(42)	15.807(16)	15.369(25)	14.948(30)
CS5	15.497(36)	14.898(12)	14.531(13)	14.180(18)

^a Figures in brackets give the internal error of each magnitude and are quoted in units of the magnitude’s least significant digit

and Suntzeff *et al.* (1999). Given the larger uncertainties in this procedure we estimate a precision of no better than ± 0.1 in the *U*-band apparent magnitudes of SN1998bu.

Thus, at a given epoch and telescope, for each available comparison star a set of magnitudes was calculated for SN 1998bu. The weighted mean magnitude in each band was then obtained. These are listed in Table 2.

2.2 Infrared Photometry

SN 1998bu yielded one of the earliest sets of *near-IR* photometry ever obtained for a supernova. Indeed, this is the first time that IR photometry for a normal type Ia event has been acquired *before* t_{Bmax} . The earliest IR observation was by Mayya & Puerari (1998) who acquired JHK photometry at -8.4 days using the Observatorio Astronomico Nacional 2.1-m telescope (+CAMILA/NICMOS 3 camera) at San Pedro Martir, Mexico. During the first season of SN 1998bu observations, IR photometry was acquired at a number of telescopes. Some of these data have been published in Jha *et al.* (1999). Preliminary IR light curves were also displayed in Meikle & Hernandez (2000). Here, we present a description of IR photometry carried out at 1.5m Telescopio “Carlos Sanchez” (TCS), Tenerife, the University of Hawaii 2.2m Telescope (UH2.2), Hawaii, the 3.8m United Kingdom Infrared Telescope (UKIRT), Hawaii and the 4.2m William Herschel Telescope (WHT), La Palma. The data are presented in Table 3.

All the TCS data were taken with the CVF IR photometer. The photometric system has been accurately characterized (Alonso *et al.*, 1994) and is very similar to the UKIRT system. For the four epochs in which the observations were carried out, a 20 arcsec. aperture

Table 2. Optical photometry of SN1998bu

Julian Day (2450000+)	Epoch ^a (d)	U	B	V	R	I	Telescope
947.43	−5.87		12.502(28) ^b	12.199(14)	11.848(16)	11.727(20)	IAC80
948.38	−4.92		12.401(75)		11.808(75)		JKT
948.43	−4.87		12.403(28)	12.117(14)	11.818(15)	11.676(19)	IAC80
949.37	−3.93		12.340(75)		11.760(75)		JKT
949.40	−3.90	11.99(20)	12.300(40)	12.070(30)	11.770(40)	11.660(50)	NOT
950.41	−2.89	11.99(20)	12.250(50)		11.770(50)	11.670(50)	NOT
950.42	−2.83		12.276(75)		11.727(75)		JKT
951.37	−1.93		12.260(75)		11.698(75)		JKT
952.36	−0.94		12.239(75)		11.704(75)		JKT
953.37	+0.07		12.239(75)		11.684(75)		JKT
954.37	+1.07		12.250(75)		11.682(75)		JKT
955.36	+2.06		12.265(75)	11.881(75)	11.713(75)	11.827(75)	JKT
956.40	+3.10		12.326(75)	11.907(75)	11.721(75)	11.859(75)	JKT
957.39	+4.09	12.20(10)	12.370(75)	11.960(75)	11.739(75)	11.905(75)	JKT
958.36	+5.06	12.30(10)	12.329(75)	11.986(75)	11.809(75)	11.988(75)	JKT
958.38	+5.08		12.423(16)	11.962(19)	11.777(20)	11.912(33)	IAC80
959.40	+6.10	12.41(10)	12.470(75)	11.989(75)	11.858(75)	12.055(75)	JKT
963.66	+10.36		12.817(26)	12.298(12)	12.249(21)	12.287(30)	WIYN
964.39	+11.09		12.880(75)	12.298(75)	12.261(75)	12.327(75)	JKT
965.66	+12.36		12.920(35)	12.419(16)	12.350(24)	12.352(25)	WIYN
966.38	+13.08		13.104(75)	12.448(75)	12.398(75)	12.398(75)	JKT
968.38	+15.08		13.352(32)	12.558(19)	12.414(25)	12.332(26)	IAC80
968.72	+15.42	13.44(10)	13.367(27)	12.609(12)	12.481(16)	12.309(18)	WIYN
969.34	+16.04		13.381(75)	12.644(75)	12.419(75)		JKT
969.42	+16.12		13.498(36)	12.616(20)	12.431(24)	12.284(25)	IAC80
969.70	+16.40	13.76(10)	13.480(31)	12.650(14)	12.480(15)	12.275(20)	WIYN
970.34	+17.04		13.487(75)	12.719(75)	12.443(75)		JKT
971.33	+18.03		13.607(75)	12.784(75)	12.444(75)		JKT
972.35	+19.05		13.717(75)	12.834(75)	12.452(75)		JKT
972.68	+19.38	14.16(10)	13.821(28)	12.791(12)	12.489(17)	12.200(18)	WIYN
973.33	+20.03		13.782(75)	12.888(75)	12.465(75)		JKT
974.33	+21.03		13.912(75)	12.958(75)	12.472(75)		JKT

Table 3. Infrared photometry of SN1998bu

Julian Day (2450000+)	Epoch ^a (d)	<i>J</i>	<i>H</i>	<i>K</i>	Telescope	Observer
949.40	−3.8	11.55(3) ^b	11.59(3)	11.42(3)	TCS	EXPORT team
950.40	−2.8	11.68(3)	11.86(3)	11.44(3)	TCS	EXPORT team
952.74	−0.5	11.71(4)	11.88(4)	11.63(3)	UKIRT	A. Chrysostomou
953.40	0.2	11.89(5)	11.95(5)	11.60(5)	TCS	P. Hammersley
955.40	2.2	11.87(5)	11.83(5)	11.66(5)	TCS	P. Hammersley
957.40	4.2	12.06(5)	11.88(5)	11.61(5)	TCS	P. Hammersley
958.40	5.2	12.05(5)	11.96(5)	11.75(5)	TCS	P. Hammersley
959.84	6.6	12.42(3)	11.97(3)	11.88(3)	UKIRT	T. Geballe
970.35	17.2	—	11.75(5)	11.84(4)	WHT	C. Benn
976.77	23.6	13.08(1)	11.74(2)	11.92(2)	UH2.2	W. Vacca

^a Relative to $t_{Bmax} = 1998 \text{ May } 19.8 \text{ UT}$.

^b Figures in brackets give the internal error of each magnitude and are quoted in units of the magnitude's least significant digit

and a chop throw of about 35 arcsec. at 6.7 Hz were employed. Conditions were judged to be photometric on all four nights, and that the photometry accuracy was no worse than $\pm 3\%$. The data were reduced using the IAC data reduction program TCSPHOT. Absolute calibration was by means of repeat measurements of a sequence of standard stars at a range of air-masses. The stars were BS3304, BS4039, BS4883, BS5384, BS5423A and BS6538A. Error estimates are based on the statistical error in the measurement of the supernova together with a smaller contribution from the measurement of the calibration sources. TCS observations were also made on 2 successive nights by the EXtra-solar Planet Observational Research Team (EXPORT) during the 1998 international time of the Canary Islands Observatories.

The UH2.2 observations were made with the QUIRC camera, which contains a 1024x1024 HgCdTe array. The plate scale is 0.189''/pixel. A 7 point dither pattern was used, chopping to sky after each individual exposure. Sky frames and flat fields were made from these offset sky fields. The airmass ranged between 1.2 and 1.3. The night was photometric, and observations of the following standard stars were made to compute the magnitudes: FS21,

FS23, FS27, and FS35. The magnitudes of the FS stars (as well as the additional stars in the fields of FS23 and FS35) given by Hunt *et al.* (1998) were used for transforming between instrumental and intrinsic magnitudes. Instrumental magnitudes were computed using an aperture of 15 pixels in radius, with a background aperture of 20–30 pixels. The seeing was typically 0.7–0.8″.

The UKIRT observations were made with the IRCAM3 camera which uses a 256x256 InSb array. The plate scale was 0.286″/pixel and the seeing was typically 1.5″. The WHT observations were made with the WHIRCAM camera which also uses a 256x256 InSb array. The plate scale is 0.240″/pixel and the seeing was typically 0.8–0.9″. For both the UKIRT and WHT observations a 5 point dither pattern was used. The data were reduced using the package IRCAMDR (Aspin 1996). Calibration of the UKIRT data was by means of the standard stars HD84800 (19 May) and FS20 (26 May), and the WHT data by means of FS25. For the UKIRT and WHT images, instrumental magnitudes were computed by increasing the aperture size until the supernova to standard ratio converged to a constant value ($\pm 1\%$). This was usually attained for aperture radii of 10–15 pixels.

2.3 Polarimetry

During the nights of 15–17 May 1998, *UBVRI* polarimetric observations were taken of SN 1998bu using the Turpol instrument, mounted on the 2.5 m Nordic Optical Telescope (NOT), La Palma, Spain. The observations were carried out by EXPORT members and data-reduction are discussed in detail in Oudmaijer *et al.* (2000).

The light from the direction of SN 1998bu was relatively strongly polarized (see Table 4). We wish to decide whether the polarization is intrinsic to the source, due to Galactic dust extinction, or extinction within M 96 itself. Time-variability in the polarization would have proven that it was intrinsic to the source, but no variation was detected over the three nights. Field stars near to M 96 showed little degree of polarization. This is consistent with the dust maps of Schlegel *et al.* (1998) which indicate that the extinction contribution from our Galaxy is small. It appears, therefore, that most of the polarization must have been produced within M 96. This is important, since the polarization as a function of wavelength behaved similarly to that seen for normal interstellar polarization *i.e.* the data follow the Serkowski model (R. Oudmaijer, personal communication). This indicates that the ISM of M 96 is somewhat similar to that of the Milky Way. In Section 3, we show that SN 1998bu is highly reddened and that most of this reddening probably arises from dust extinction within M 96.

Table 4. Polarimetry of SN1998bu (EXPORT team)

Julian Day (2450000+)	Epoch ^a (d)	Band	POL (%)	Error (%)	Posn. Angle (deg.)	Error (deg.)
949.40	−3.90	U	1.227	0.076	186.3	1.8
949.40	−3.90	B	1.597	0.072	184.6	1.3
949.40	−3.90	V	1.695	0.105	179.1	1.8
949.40	−3.90	R	2.101	0.068	180.3	0.9
949.40	−3.90	I	1.871	0.145	173.4	2.2
950.41	−2.89	U	1.091	0.075	184.2	2.0
950.41	−2.89	B	1.469	0.074	181.2	1.4
950.41	−2.89	V	1.842	0.101	177.8	1.6
950.41	−2.89	R	1.894	0.065	177.9	1.0
950.41	−2.89	I	1.788	0.107	174.5	1.7
951.40	−1.90	U	1.222	0.079	182.3	1.9
951.40	−1.90	B	1.689	0.073	181.0	1.2
951.40	−1.90	V	1.757	0.108	178.6	1.8
951.40	−1.90	R	1.965	0.105	179.5	1.5
951.40	−1.90	I	1.668	0.129	176.5	2.2

^a Relative to $t_{Bmax} = 1998 \text{ May } 19.8 \text{ UT}$.

It therefore seems likely that observed polarization is associated with interstellar material within M 96.

2.4 Optical Spectroscopy

Optical spectroscopy was acquired using the ISIS spectrograph of the William Herschel Telescope (WHT), the IDS spectrograph of the Isaac Newton Telescope (INT) and the Hydra spectrograph of the Wisconsin-Indiana-Yale-NOAO Telescope (WIYN). The log of observations is given in Table 5. The spectra were reduced by means of the package FIGARO (Shortridge *et al.*, 1995). Debiasing and flat-fielding were carried out in the usual manner.

Wavelength calibration was by means of arc lamp spectra, and the uncertainty was typically less than ± 1 Å. The spectra were relatively fluxed by comparison with the flux standard Feige 34. However, absolute fluxing was more difficult owing to variable observing conditions which resulted in uncertain amounts of vignetting of the target and standard by the slit. To correct for this systematic error, we used the *BVR* magnitudes obtained from the JKT images. Transmission functions for the *B*, *V* and *R* bands were constructed by multiplying the JKT filter functions by the CCD response and the standard La Palma atmospheric transmission function. The relatively-fluxed spectra were then multiplied by the net transmission functions, and the resulting total flux within each band compared with JKT-derived magnitudes corresponding to the same epochs. Thus, correction (scaling) factors were obtained for each spectrum. Apart from the earliest spectrum (−6.8 d), *BVR* magnitudes corresponding to the spectroscopy epochs were obtained either from actual simultaneous observations or by interpolation within the JKT data. Fluxing of the −6.8 d spectrum was less certain as it was obtained 2 days before the earliest JKT photometry point. We therefore used photometry gleaned from the IAU circulars and from Suntzeff *et al.* (1999) and Jha *et al.* (1999) to estimate the *BVR* magnitudes at −6.8 d.

Scaling factors ranged from $\times 0.83$ to $\times 2.23$. The scaling factor closest to unity ($\times 0.94$) was for the −3.8 d spectrum. This was expected since the flux scale for this spectrum had already been corrected using a low-resolution spectrum taken through a very wide (7 arcsec.) slit. For a given epoch, the scaling factors for each band agreed to within $\pm 5\%$ demonstrating good internal consistency for the procedure. The relatively-fluxed spectra were therefore multiplied by the geometric mean of the scaling factors for each epoch. Including the uncertainty in the photometry, we estimate that the fluxing accuracy is better than $\pm 10\%$ except for −6.8 d where the error is probably closer to $\pm 15\%$. The optical spectra are shown in Figure 2. The −6.8 d spectrum is the earliest reported for SN 1998bu.

2.5 Infrared Spectroscopy

IR spectroscopy at UKIRT was obtained on 1998 June 24.2 UT (+35.5 d) using CGS4, its 40 l/mm grating and a 0.61" (1 pixel) wide slit (see Table 5). The spectra were sampled every 1/2 pixel; the resolution of the spectrometer was approximately 370 km/s in the *IJ*-bands and 450 km/s in the *H* band. During the observations the telescope was nodded 7.5 arcsec. along the slit.

The spectra were reduced using the standard procedures of the package FIGARO, in-

Table 5. Log of optical and infrared spectroscopy of SN1998bu

Julian Day (+2450000)	Date UT ^a (1998)	Epoch ^b (d)	Telescope/Instrument	$\lambda\lambda$ (Å)	$\Delta\lambda^c$ (Å)	Observer
946.40	May 12.90	−6.8	WHT/ISIS	3590–9097	5.8	J. Iglesias-Paramo
949.38	May 15.88	−3.8	INT/IDS	3300–9072	13	P. Sorensen ^d
951.40	May 17.90	−1.8	INT/IDS	3300–9081	13	EXPORT
952.40	May 18.90	−0.8	INT/IDS	3207–9460	6.6	D. Pollacco
964.72	May 31.22	+11.5	WIYN/Hydra	3541–5573	4.0	P.S. Smith
966.68	June 2.18	+13.5	WIYN/Hydra	4910–10265	5.2	D. Willmarth
972.40	June 7.90	+19.2	INT/IDS	3602–9298	6.6	D. Pollacco
988.75	June 24.25	+35.5	UKIRT/CGS4	8175–20966	12.5 & 41	T. Geballe

^a *Start* time for integrations on SN 1998bu.^b Relative to $t_{Bmax} = 1998 \text{ May } 19.8 \text{ UT}$.^c Spectral resolution. The $\Delta\lambda$ values for UKIRT/CGS4 are for 10,000 Å and 16,500 Å respectively.^d Observations carried out during EXPORT telescope time

cluding optimal extraction (Horne, 1986). Wavelength calibration was by means of an arc spectrum, and is judged to be accurate to better than 2 Å in the IJ-bands and 3 Å in the H-band. Relative fluxing was by comparison with spectra of BS 4281 (*IJ*-bands) and BS 4079 (*H*-band). For BS 4281 (F5V) we assumed $J=+5.845$ and a temperature of 6540 K. For BS 4079 (F6V) we assumed $J=+5.770$ and a temperature of 6450 K. Final absolute fluxing was achieved using the composite *J*- and *H*-band light curves described in section 3.2. From these we obtain $J = +13.18 \pm 0.10$ and $H = +12.24 \pm 0.10$ at the epoch of the IR spectra. Magnitudes were then derived from the IR spectra using the combined filter passband plus atmospheric transmission response functions provided on the UKIRT web pages together with the absolute spectrum of Vega. On comparison with the light curve-derived values it was found that the spectrum-derived magnitudes were too faint by factors of $\times 1.02$ in *J* and $\times 1.23$ in *H*. The fluxes of the spectra were therefore multiplied by these factors. The *I*-band spectrum overlapped the *J*-band spectrum in the 10,000–11,000 Å region. We multiplied the *I*-band flux by $\times 1.14$ to bring it into agreement with the *J*-band. We believe the final fluxing is accurate to $\pm 15\%$. The IR spectrum is displayed in Figure 3. It spans 8,175–20,966 Å.

(The short wavelength coverage of CGS4 now overlaps the typical long wavelength limit of optical spectrographs, providing access to the poorly explored 0.9–1.0 μm region.)

3 RESULTS

3.1 Spectra

3.1.1 Optical Spectra

The optical spectra demonstrate that SN 1998bu was a spectroscopically normal, but highly reddened type Ia supernova. This is illustrated in Figure 4 where we compare the spectra of SN 1998bu at maximum light with those of the normal type Ia SNe 1981B (Branch *et al.*, 1983) and 1994D (Meikle *et al.*, 1996). The three spectra are quite similar. The main difference is due to the greater reddening of SN 1998bu (see below). Redward of 5000 Å, SN 1998bu and SN 1981B have greater similarity, although the calcium triplet absorption around 8250 Å is considerably deeper in SN 1981B. At shorter wavelengths the fine structure of the SN 1998bu spectrum are generally closer in appearance to those of SN 1994D. Jha *et al.* (1999) pointed out the existence of an unidentified absorption feature blueward of the CaII H & K absorption, and suggested it could be due to silicon or calcium. This feature is clearly visible at $\sim 3,700$ Å in all the SN 1998bu spectra up to t_{Bmax} , including the first spectrum at -6.8d (Figure 2). The feature is not present in the maximum light spectrum of SN 1981B but is very strong in SN 1994D at the same epoch (Figure 4). However, later spectra (day +9 (Jha *et al.*; day +11.5 (this work)) show the feature has weakened considerably. By day +19.2d it has essentially vanished.

3.1.2 Infrared Spectrum

The strong P Cygni feature at 8,175–8,700 Å is due to the calcium triplet (Filippenko 1997). At $\sim 10,000$ Å there is a particularly prominent, isolated feature. In the rest frame of the host galaxy the feature peaks at 9950 ± 150 Å and has a FWHM equivalent to $\sim 8,000$ km/s. If we interpret the trough to the blueward side as being the absorption component of a P-Cygni profile then the blueshift of the trough is $8,170 \pm 570$ km/s. P. Höflich (private communication) suggests that this line can be identified with the very strong Fe II $z^4F_4 - b^4G_5$ 9,997.56 Å line. This line is predicted in some of the model spectra of Wheeler *et al.* (1998). Between 10,000 and 12,000 Å, SN 1998bu exhibits the dramatic drop responsible for

the typical red J–H colour of type Ia events at this time. Many of the other features in the IR spectrum are probably due to singly and doubly-ionized cobalt and iron (Bowers *et al.* 1997).

In Figures 5 & 6 we compare the IR spectrum of SN 1998bu with those of other SN Ias over a range of epochs (Bowers *et al.* 1997). The spectrum nearest in epoch to the SN 1998bu +35.5 d spectrum is the +40 d spectrum of SN 1992G. The two spectra are similar. It can be seen that the prominent Fe II feature at $\sim 10,000 \text{ \AA}$ is quite common in early time type Ia events, and persists from as early as +20 days to as late as +60 days. However, by +92 days the feature appears to weaken. It could prove to be a valuable line for determination of both abundance and velocity distribution (P. Höflich, private communication.)

3.2 Light Curves

3.2.1 Optical Light Curves

The optical photometry (Table 2) is plotted as light curves in Figure 7. The shapes of the light curves are typical for a normal type Ia supernova, and agree with those presented by Suntzeff *et al.* (1999) and Jha *et al.* (1999). The *BRI* magnitudes and epochs at maximum light were estimated by fitting low order polynomials. In the *V* band, the light curve is not well sampled around maximum. We therefore fitted the *V* template of Leibundgut (1988) to find the epoch of maximum light in this band. The values are shown in Table 6. Maximum light in the *B*-band occurred on May 19.8 ± 0.5 days (UT) and we adopt this as the fiducial $t_{Bmax}=0$ days. Suntzeff *et al.* (1999) found t_{Bmax} to be on May 19.4 ± 0.5 (UT) and Jha *et al.* obtained May 19.3 ± 0.8 days. Thus all three estimates agree to within the uncertainties.

From our *B*-band light curve we find the decline rate parameter $\Delta m_{15}(B) = 1.06 \pm 0.05$. This is consistent with the observed values yielded by the *B*-band light curves of Suntzeff *et al.* (1999) and Jha *et al.* (1999). Phillips *et al.* (1999) point out that the decline rate is a weak function of extinction. In their Equ. 6 they provide a correction relation which we find yields a correction of +0.03 for SN 1998bu (see also section 3.4). We therefore adopt $\Delta m_{15}(B) = 1.09 \pm 0.05$.

The *VRI* fluxes peaked at, respectively, $+1.7 \pm 1.1$ d, $+0.3 \pm 0.7$ d, and -3.0 ± 0.7 d. This is consistent with Suntzeff *et al.* (1999) who report maxima at $+1.2 \pm 0.7$, $+0.6 \pm 0.7$ and -3.4 ± 1.1 days for *VRI* respectively, and with Jha *et al.* (1999) who find the V-maximum to have occurred at $+1.6 \pm 1.3$ days. This behavior has been noted in other type Ias such as

Table 6. Epochs and magnitudes at maximum light

Julian Day (+2450000)	Epoch ^a (d)	Waveband	Apparent Mag.	De-reddened Mag.	Absolute Mag.
953.3(0.5)	0.0	B	12.24(08) ^b	10.90(17) ^c	−19.35(25) ^d
955.0(1.0)	+1.7	V	11.88(10)	10.88(14)	−19.37(23)
953.6(0.5)	+0.3	R	11.68(08)	10.93(11)	−19.32(21)
950.3(0.5)	−3	I	11.66(08)	11.18(10)	−19.07(21)
948.0(2.0)	−5	J	11.55(25)	11.27(25)	−18.98(31)
948.0(2.0)	−5	H	11.60(25)	11.41(25)	−18.84(31)
948.0(2.0)	−5	K	11.40(25)	11.29(25)	−18.96(31)

^a Relative to $t_{Bmax} = 1998 \text{ May } 19.8 \text{ UT}$.

^b Figures in brackets give the internal errors in units of the least significant two digits.

^c The error given in this column is the combination of the random photometric error and the systematic error in the reddening correction.

^d The error given in this column is the combination of the random photometric error and the systematic error in the distance and reddening correction.

SN 1990N and SN1992A (Suntzeff 1993, Leibundgut 1998, Lira *et al.* 1998). Clearly, this is not the behavior of a simple cooling blackbody, where the maximum would occur later at longer wavelengths. That the photosphere is not a pure blackbody is confirmed by the contemporary spectra (Figure 2). We note that for SN 1998bu the times between maxima in different bands do *not* agree with the analysis of SN Ia light curves by Schlegel (1995). He obtained $t_{Rmax}-t_{Imax} + 1.6 \text{ d}$, $t_{Rmax}-t_{Vmax} + 3.6 \text{ d}$ and $t_{Imax}-t_{Vmax} + 2.0 \text{ d}$, while our results for SN 1998bu are +3.3, −1.4 and −4.7 d respectively. We also see a pronounced second maximum in *I* at about +25 d together with a corresponding inflection in *R*. Again, this behavior has been seen in other type Ias (*e.g.* Ford *et al.* 1993).

3.3 Infrared Light Curves.

In Figure 8 we show both the optical and infrared light curves. The latter were obtained by plotting our IR photometry (Table 3) together with data from Mayya & Puerari (1998) and Jha *et al.* (1999). These data constitute one of the most complete early-time infrared light curves obtained for a type Ia supernova. As mentioned above, it is the first time that IR photometry for a normal type Ia event has been acquired *before* t_{Bmax} . We find that the

first maximum in the IR light-curves occurs at about -5 d. Thus, there is a trend in which the epochs of first maximum occur earlier as we move from the *R*-band through *I* and into the IR. We also show in Figure 8 the *JHK* template light curves of Elias *et al.* (1985). (We have slightly truncated Elias *et al.*'s original templates so that the earliest epoch of the template corresponds to Elias *et al.*'s earliest observation.) The position of these templates were fixed on the time axis assuming that the fiducial time, $t_0 = 0$, of Elias *et al.* corresponds to -6.25 days. The IR light curves have been shifted vertically to provide the best match to the data. A detailed discussion of the IR light curves is given in Meikle (2000).

3.4 Extinction Correction, Absolute Peak Magnitudes and a Value for H_0

SN 1998bu exhibited an unusually high degree of reddening. At t_{Bmax} , $B - V = 0.53 \pm 0.13$, much redder than the typical $B - V \approx 0$ of SNe Ia (Branch, 1998). However, both the light curve shapes and the spectral features of SN 1998bu are typical of a type Ia event; this and the results of our polarimetry lead us to conclude that SN 1998bu was indeed a normal type Ia supernova, but that it was heavily reddened by dust. Estimation of the amount of reddening is, however, a difficult issue. Several methods have been considered.

One way is to use the relation between the equivalent width (*EW*) of interstellar lines such as Na I D and the colour excess, $E(B - V)$ (Barbon *et al.* 1990). Recently, Munari & Zwitter (1997) produced an improved determination of the relationship for the Milky Way by measuring $E(B - V)$ for 32 O-type and B-type stars. The spectra of SN 1998bu exhibit narrow Na I D absorption lines in the rest frames of both the Milky Way and M 96 (Munari *et al.* 1998). The *EW*s are, respectively, 0.19 Å and 0.35 Å. Centurion *et al.* (1998) also reported *single* Na I lines in the Milky Way and M 96. With these data, and assuming that Munari & Zwitter (1997) relation is also valid in M 96*, we obtain a total colour excess (*i.e.* including Galactic reddening) for SN 1998bu of $E(B - V) = 0.21$, or $A_V = 0.65$ assuming $R_V = 3.1$. This is a significantly lower value than that found by consideration of the SN colours (see below). Moreover, Munari & Zwitter (1997) warn that the use of the Na I D1 line to account for interstellar extinction is only valid when the line can be modeled with a single Gaussian component. When absorption is multi-component, their relation provides an *upper limit* only for $E(B - V)$. Thus, as also pointed out by Suntzeff *et al.* (1999), this is inconsistent with the SN-colour derived values.

* Polarimetry results suggest that the ISM in M 96 is similar to that of our own Galaxy, see sub-section 2.3

A different procedure is that followed by Phillips *et al.* (1999). They use a technique based on the fact that all type Ia events show a very similar $B - V$ evolution between 30 and 90 days after V -maximum. For SN 1998bu, they find a total $E(B - V) = 0.355 \pm 0.030$ or $A_V = 1.10 \pm 0.09$ ($R_V=3.1$). Another SN-colour procedure is the Multicolor Light Curve Shape method, developed by Riess *et al.* (1996). It is a multi-template ($BVRI$) method that uses a training set of well-studied SNe Ia to produce a “standard SN Ia”, and deviations from this fiducial event are quantified as a function of changes in luminosity and extinction. Application of this method by Jha *et al.* (1999) to SN 1998bu gives a total $E(B - V)=0.30$ or $A_V=0.94$, consistent with the value obtained by Phillips *et al.*. Yet another SN-colour method has been proposed by Krisciunas *et al.* (2000). They compared the $V - IR$ colours of SN 1998bu with those of less-reddened SNe Ia and infer $A_V = 1.05 \pm 0.06$, again consistent with Phillips *et al.*.

One further approach is to compare SN 1998bu with SN 1981B. As pointed out in Meikle & Hernandez (2000) and in Section 3.1.1 (above), the detailed optical spectral features of these two SNe Ia around t_{Bmax} are very similar, especially redward of 5000 Å (see Figure 2). The major difference between the two events is the overall spectral slope. We therefore assume that the Supernovae are intrinsically identical and that the difference in slope is due to extinction. We modified a SN 1981B spectrum taken at t_{Bmax} (Branch *et al.* 1983) by simultaneously scaling the flux by wavelength-dependent and wavelength-independent factors. The behavior of the wavelength-dependent factor is taken to be the Cardelli *et al.* (1989) extinction law. This procedure was followed until a good match was obtained between the SN 1981B spectrum and one of SN 1998bu at -0.8 d. This was achieved with a *difference* in A_V between the two SNe Ia of $\Delta A_V = 0.60 \pm 0.06$, or $\Delta E(B - V) = 0.19 \pm 0.02$. Clearly, this represents a lower limit to the SN 1998bu extinction. The matched spectra are shown in Fig. 9. It can be seen that there are some differences between the individual spectral features but that they are generally quite small. However, as mentioned earlier, the calcium triplet absorption is significantly deeper in SN 1981B. Using their $B - V$ evolution method, Phillips *et al.* (1999) give a total $E(B - V) = 0.13 \pm 0.03$ for SN 1981B. Adding this to the extinction difference between SNe 1981B and 1998bu, we obtain for SN 1998bu $E(B - V) = 0.32 \pm 0.04$, or $A_V = 1.0 \pm 0.11$, in good agreement with the SN-colour derived values described above. We used this value with the Cardelli *et al.* (1989) law, $R_V = 3.1$, and a distance modulus of

30.25 ± 0.18 (see Introduction) to determine the absolute intrinsic peak magnitudes. These are shown in Table 6.

We find that SN 1998bu peaked at $V = -19.37 \pm 0.23$ (see Table 6 for other bands). This is 0.26 ± 0.30 and 0.05 ± 0.32 fainter than the values found by, respectively, Suntzeff *et al.* and Jha *et al.* Applying our values for the absolute peak BVI magnitudes and reddening-corrected $\Delta m_{15}(B)$ to Phillips *et al.*'s (1999) relations (17–19) we obtain $H_0 = 70.4 \pm 4.6$ km/s/Mpc. Suntzeff *et al.* derive $H_0 = 64 \pm 2.2(int.) \pm 3.5(ext.)$ km/s/Mpc from their SN 1998bu light curves. The barely significant difference between our value and that of Suntzeff *et al.* can be explained by the choices of extinction correction and distance modulus.

4 SUMMARY

We have presented first-season $UBVRIJHK$ photometry and $UBVRI$ polarimetry of the nearby type Ia SN 1998bu. Also presented are a set of optical spectra spanning $t = -6.8 d$ to $t = +19.2d$ plus a single IR spectrum at $t = +35.5 d$. The optical light curve shapes are typical of a normal type Ia supernova. In addition, de-reddening of the -0.8 day optical spectrum using the standard Galactic extinction law (Cardelli *et al.* 1989) produces a spectrum which is highly similar to those of classic SNe Ia. This suggests strongly that the very red colour of SN 1998bu is due to extinction. It is also likely that the relatively strong polarization is associated with grains within M 96 along the line of sight. We conclude that both the light curve shapes and spectra indicate that SN 1998bu is a *normal* type Ia supernova.

The $BVRI$ peak magnitudes we obtained are consistent with those of Suntzeff *et al.* (1999) and Jha *et al.* (1999). We de-reddened the photometry using the Cardelli *et al.* law with $R_V = 3.1$ and A_V derived from estimates of intrinsic SN Ia colours. The absolute peak magnitudes were then found using a distance modulus of 30.25 ± 0.18 . We find that SN 1998bu peaked at $V = -19.37 \pm 0.23$ (see Table 6 for other bands). Our results yield a value for the Hubble Constant of $H_0 = 70.4 \pm 4.3$ km/s/Mpc.

Combination of our IR photometry with those of Jha *et al.* provides one of the most complete early-phase IR light curves for a SN Ia published so far. In particular, SN 1998bu is the first normal SN Ia for which good pre- t_{Bmax} IR coverage has been obtained. It reveals that the JHK light curves peak about 5 days earlier than in the B -band. Secondary maxima are seen in the IJK bands, with a corresponding inflection in the R -band. For further details see Meikle (2000).

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FIGURE CAPTIONS

Figure 1: SN 1998bu in M 96 in the R -band, 1998 June 8 (WIYN). The five comparison stars (CS) are labelled. The field of view is 6.5×6.5 arcmin. North is up and East is to the left.

Figure 2: Optical spectra of SN 1998bu taken at the WHT and INT (La Palma) and the WIYN Telescope (Kitt Peak) (see Table 5 for details). The spectra have not been corrected for redshift or reddening. The epochs are with respect to $t_{Bmax} = 1998 \text{ May } 19.8 = 0$ days. For clarity, the spectra have been displaced vertically. The dotted lines on the left side indicate zero flux for each of the spectra. For +19.2 d zero flux is at the x-axis. The lowest dotted line indicates zero flux for both the +11.5 d and +13.5 d spectra. In general, the absolute fluxing is accurate to $\pm 10\%$. For -6.8 d the uncertainty is closer to $\pm 15\%$.

Figure 3: Infrared spectrum of SN 1998bu taken at UKIRT at +35.5 days. The epoch is with respect to $t_{Bmax} = 1998 \text{ May } 19.8 \text{ UT}$. The data have not been corrected for redshift or reddening.

Figure 4: Illustration of the high degree of similarity in the optical spectra of the type Ia Supernovae SNe 1981B, 1994D and 1998bu. The epochs are all within about 1 day of t_{Bmax} . To aid the comparison the spectra have been scaled and shifted vertically by arbitrary amounts and have been wavelength shifted to the local standard of rest for the respective supernovae. Their zero flux axes are indicated by the dotted lines on the left hand axis. The SN 1981B spectrum is from Branch *et al.* (1983) and is courtesy of B. Leibundgut and P. Nugent. The SN 1994D spectrum is from Meikle *et al.* (1996).

Figure 5: Infrared spectrum of SN 1998bu compared with those of other type Ia Supernovae at a range of epochs (Bowers *et al.*, 1997). Also shown is the IR spectrum of SN 1998bu at ~ 25 d published by Jha *et al.* (1999). The spectra have been shifted vertically and scaled for clarity. Their zero flux axes are indicated by the dotted lines on the left hand axis. The spectra have been wavelength shifted to the local standard of rest for the respective Supernovae.

Figure 6: As Figure 5 but expanded to reveal the detail in the spectra longward of $11,000 \text{ \AA}$.

Figure 7: Optical light curves for SN 1998bu. For clarity they have been vertically displaced by the amounts indicated. The epoch of maximum blue light, t_{Bmax} , corresponds to 1998 May 19.8 UT.

Figure 8: Infrared and optical light curves for SN 1998bu. For clarity they have been displaced vertically by arbitrary amounts. The IR photometry was obtained at the OAN (Mayya & Puerari (1998)), TCS, IRTF, UKIRT and WHT telescopes. The optical light curves are as plotted in Figure 7. Also shown are template light curves in BV (Leibundgut 1988), RI (Schlegel 1995) and JHK (Elias *et al.* 1985). The $BVRI$ templates were shifted in both axes to give the best match to the data. The JHK templates were shifted only vertically. Their horizontal position was fixed by the epoch of t_{Bmax} as indicated in Elias *et al.* (see text).

Figure 9: This illustrates the determination of the relative extinction to SNe 1981B and 1998bu. The solid and dotted lines show the optical spectra of SNe 1998bu and 1981B respectively. The dashed line shows the SN 1981B spectrum reddened by $A_V = 0.60 \pm 0.07$ to match that of SN 1998bu, using the extinction law of Cardelli *et al.* (1989), with $R_V = 3.1$.

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